

*A Final Report for*

STUDIES OF EXTRA-SOLAR OORT CLOUDS AND THE  
KUIPER DISK -- CONTRACT NAGW-3023

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## INTRODUCTION

This is the final report for NAGW-3023 (SwRI Project 15-4971), *Studies of Extra-Solar Oort Clouds and the Kuiper Belt*, (S.A. Stern, PI).

We are conducting research designed to enhance our understanding of the evolution and detectability of comet clouds and disks. This area also holds promise for improving our understanding of outer solar system formation, the bombardment history of the planets, the transport of volatiles and organics from the outer solar system to the inner planets, and to the ultimate fate of comet clouds around the Sun and other stars. According to “standard” theory, both the Kuiper Belt and the Oort Cloud are (at least in part) natural products of the planetary accumulation stage of solar system formation. One expects such assemblages to be a common attribute of other solar systems. Therefore, searches for comet disks and clouds orbiting other stars offer a new method for inferring the presence of planetary systems.

This project consists of two efforts: (1) observational work to predict and search for the signatures of Oort Clouds and comet disks around other stars; and (2) modelling studies of the formation and evolution of the Kuiper Belt (KB) and similar assemblages that may reside around other stars, including  $\beta$  Pic. These efforts are referred to as Tasks 1 and 2. The main collaborators with PI Stern in Task 1 are CoIs Drs. David Weintraub (Vanderbilt U.) and Mike Shull (U. Colorado). The main collaborator in Task 2 has been CoI Dr. Glen Stewart (U. Colorado).

## PROGRESS

### Task 1: Studies Related to Observations of Comet Belts and Clouds

The study of main sequence stellar disks is now about a decade old. Although the existence of such disks is well established, many questions remain open. Our work regarding comet cloud detection around other stars has included work using constraints from  $\gamma$ -Ray Burst statistics to constrain the fraction of galactic disk stars with Oort-like clouds (Stern & Shull 1994), studies of Fomalhaut (Stern et al. 1994), and submm/mm-wave bolometry of a small sample of nearby IR excess stars (Weintraub & Stern 1994).

Last year we completed 2 new observing runs at the IRAM and SEST submm telescopes to study one of the best-known IRAS IR-excess comet cloud candidates,  $\alpha$  PsA (Fomalhaut),  $\tau$  Ceti,  $\beta$  Pic, and HD98800. Our HD98800 measurements were published in an IAU Circular (IAUC 6003; June 1994).

In parallel with our observing program, two papers on theoretical subjects related to comet cloud and planetary detection have been completed, submitted, and published. In the first, PI Stern developed a new method for directly detecting planets. This method is based on the fact that giant impacts, like the one that formed the Earth-Moon system, cause the target planet to become IR-luminous for several hundred to several thousand years. The paper demonstrates (i) that such events will be detectable from the twin-Keck interferometer, and (ii) that in a young

star cluster like Orion, between one and a few such “hot planets” should be extant at any given time. In the second paper, PI Stern and collaborator Shull have shown that the *lack* of a galactic population of Gamma Ray Bursters (GRBs) constrains the fraction of stars in the galaxy that have Oort Clouds to  $\leq 20\%$ .

## Task 2: Collisional Modelling of the Kuiper Belt

In work completed during our first Origins research cycle, we made an initial study to evaluate the importance of impacts in the Kuiper disk. This work represented an outgrowth of Oort Cloud modeling performed by one of us (Stern 1988), who explored the collision rates of comets in the Inner and Outer Oort clouds. The essential rationale for a similar study in the Kuiper disk was based on the  $10^3 - 10^4$  times higher number density of comets and the 10 times higher average orbital speeds in the Kuiper disk compared to the Oort Cloud. Together these two factors imply that collision rates should be 4 to 5 orders of magnitude higher in the Kuiper disk than in the Oort cloud.

With this motivation, we constructed a simple, first-order model to estimate collision rates in the Kuiper belt (Stern 1995, 1996a,b). Four particularly intriguing conclusions we obtained are:

- Using disk masses and average eccentricity/inclination values consistent with those needed to resupply the short-period comet population (cf., Duncan, Levison, & Budd 1995), we found that comet-comet collisions do occur in the disk today, but at a rate of only  $\sim 0.1 - 10 \text{ yr}^{-1}$ , depending on the various model parameters. This corresponds to a present-day source generating of order  $10^{15} - 10^{18} \text{ g yr}^{-1}$  of dust. Such collisions initially produce dust trails, which dissolve under radiation forces into a more diffuse, disk-like dust structure.
- That the rate of collisions in the Kuiper disk today is too low to grow QB<sub>1</sub>-sized bodies over the age of the solar system. That is, comet-sized bodies cannot accumulate enough mass (by several orders of magnitude) to grow to QB<sub>1</sub>-sized bodies, even if *all* collisions result in growth.
- That a more massive, primordial disk containing  $3\text{-}30M_{\oplus}$  of solids between 30 and 100 AU (depending on the radial and size distribution power laws) could produce collision times short enough to permit the buildup of QB<sub>1</sub>-sized objects over the age of the solar system. A more massive, early inner disk than required ( $\leq 0.1M_{\oplus}$ ) to supply the short-period comets today would be consistent with both a disk whose radial surface mass density that was smoothly declining (instead of truncated) beyond 30 AU, and the more extended, massive disks implied by observations of some T Tauri stars. Whether this intriguing, preliminary finding bears merit depends on whether it is sustained after a comprehensive collisional model is in place.
- Owing to the steepness of reasonable heliocentric radial surface-mass density power laws,

collisional times beyond  $\sim 80 - 100$  AU far exceed the age of the solar system for essentially all plausible disk masses. This led us to several predictions: (i) If the disk of comets and larger planetesimals was originally massive, its unevolved remnant might be in place today beyond 80-100 AU; (ii) that this could be evidenced by a change in the population size structure or number density of objects beyond a critical distance where the collision timescale exceeds the age of the solar system; and (iii) that the present day “edge” in the solar system’s mass distribution beyond 30 AU *might* in fact be an artifact of collisional evolution in the disk.

These results imply that collisions may have played a much more important role in the young Kuiper disk than the present Kuiper disk (where collisions serve mainly as a tracer of the mass distribution). This work, which is the first (and to our knowledge the only) project exploring collisional evolution in the disk, has important implications for the interpretation of results from sophisticated but purely-dynamical Kuiper disk evolution models created by Holman & Wisdom (1992) and Levison & Duncan (1993).

Given our findings, it appears that either the present-day paradigm for the formation of Kuiper Belt is failed in some fundamental respect, or that the present-day disk is no longer representative of the ancient structure from which it evolved. In particular, it appears that the 30-50 AU region of the Kuiper Belt has very likely experienced a strong decrease in its surface mass density over time. This in turn suggests the intriguing possibility that the present-day Kuiper Belt evolved through a more erosional stage reminiscent of the disks around the A-stars  $\beta$  Pictoris,  $\alpha$  PsA, and  $\alpha$  Lyr. These results were published in *The Astronomical Journal*.

We have also used this model and a second code to estimate the detectability of IR emission from debris created by collisions. We found that eccentricities in the Kuiper Belt are high enough to promote erosion on virtually all objects up to  $\sim 30$  km, independent of their impact strength. Larger objects, such as the 50-170 km radius “QB<sub>1</sub>” population, will suffer net erosion if their orbital eccentricity is greater than  $\approx 0.05$  ( $\approx 0.1$ ) if they are structurally weak (strong). The model predicts a net collisional erosion rate from all objects out to 50 AU ranging, from  $3 \times 10^{16}$  to  $10^{19}$  g yr<sup>-1</sup>, depending on the mass, population structure, and mechanical properties of the objects in the Belt. We find two kinds of collisional signatures that this debris should generate. First, there should be a relatively smooth, quasi-steady-state, longitudinally isotropic, far IR (i.e.,  $\sim 60$   $\mu$ m peak) emission near the ecliptic in the solar system’s invariable plane ecliptic, caused by debris created by the ensemble of ancient collisions. The predicted optical depth of this emission could be as low as  $7 \times 10^{-8}$ , but is most likely between  $3 \times 10^{-7}$  and  $5 \times 10^{-6}$ . We find that this signature was most likely below IRAS detection limits, but that it should be detectable by both ISO and SIRTf. Second, very recent impacts in the disk should produce short-lived, discrete clouds with significantly enhanced, localized IR emission signatures superimposed on the smooth, invariable plane emission. These discrete clouds should have angular diameters up to 0.2 deg, and annual parallaxes up to 2.6 deg. Individual expanding clouds (or trails) should show significant temporal evolution over timescales of a few years. As few as zero or as many as several  $10^2$  such clouds

may be detectable in a complete ecliptic survey at ISO's sensitivity, depending on the population structure of the Kuiper Belt. This work was recently accepted for publication in *Astronomy & Astrophysics*.

These two papers were also accompanied by an invited review, which is to appear in the *Planetary Ices* book, summarizing the present state of knowledge about the Kuiper Belt and Pluto, and review on the Origin of Pluto which is to appear in the University of Arizona's volume, *Pluto & Charon* (1996). We also mention that PI Stern wrote a public outreach article for the popular magazine, *Astronomy* on a subject related to this research.

Additionally, PI Stern gave several invited talks summarizing the collisional modelling results obtained under the Origins program. A list of these talks is attached.

Finally, we wish to mention that in July 1995, we organized and sponsored a 2-day workshop on collisions in the Kuiper Belt. This workshop was attended by D. Davis (PSI), P. Farinella (Italy), R. Canup (U. Colorado), M. Festou (France), J. Colwell (U. Colorado), H. Levison (SwRI), and PI Stern (SwRI). The proceedings of this workshop were informally published and distributed among the participants. A copy was also sent to Origins program scientist, Trish Rogers.

## RELEVANT PUBLICATIONS

Stern, S.A., M.C. Festou, and D.A. Weintraub. A Collisionionally Evolving Disk around Fomalhaut. *Nature*, **368**, 31, 942.

Weintraub, D.A., and S.A. Stern. A Reinterpretation of Millimeter Observations of Nearby IRAS Excess Stars. *The Astronomical Journal*, **108**, 701, 1994.

The Detectability of Extrasolar Terrestrial and Giant Planets During Their Luminous, Final Accretion. S.A. Stern. *The Astronomical Journal*, **108**, 2312, 1994.

Gamma Ray Bursts Constraints on the Galactic Frequency of Extra-Solar Oort Clouds. J.M. Shull and S.A. Stern. *The Astronomical Journal*, **109**, 690, 1995.

Pluto and the Kuiper Disk. S.A. Stern. Submitted to "Ices in the Solar System." (C. DeBergh, B. Schmitt, M.C. Festou, eds.), 1995.

Collision Rates in the Kuiper Disk and Their Implications. S.A. Stern, *The Astronomical Journal*, **110**, 856, 1995.

Signatures of Collisions in the Kuiper Disk. S.A. Stern. *Astronomy & Astrophysics*, in press, 1996.

On the Origin of Pluto, Charon, and the Pluto-Charon Binary. S.A. Stern, W.B. McKinnon, and J.I. Lunine. Invited chapter for the UA Press Space Science Series volume, "Pluto & Charon," in press, 1996.

Interstellar Intruders. S.A. Stern, *Astronomy Magazine*, in press for 1996 (educational outreach).

## RECENT SCIENTIFIC PRESENTATIONS & ABSTRACTS

Collisions in the Kuiper Disk. Astronomy Luncheon Seminar. Queen's University Department of Physics. Kingston, Ontario, 2 February 1995.

Pluto, Charon, and The Kuiper Disk. Ices in the Solar System Meeting. Toulouse, France, 25 March 1995.

The Kuiper Disk: Evidence for Arrested Planetary Accretion? Laboratory for Atmospheric and Space Physics Seminar, University of Colorado, Boulder, CO, 28 September 1995.

Collisions and the Architecture of the Kuiper Belt. Kuiper Belt Workshop. Canadian Institute for Theoretical Astrophysics. Tortonto, Canada. 8 June 1996.

